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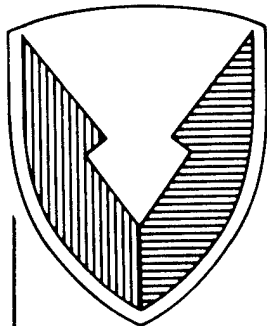
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C E N T E R

## *Technical Report*



No. 13130

**Computer-Aided Design and  
Manufacture (CAD/CAM)**

**Techniques for Optimum Preform and Finish Forging  
of Spiral Bevel Gears (Phase III)**

**Contract Number DAAK30-79-C-0071**

**September, 1985**

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) In Phase III of the program, spiral bevel gear forging dies were designed and manufactured using the CAD/CAM techniques, developed in Phase I of the study. The gear selected for the project was a 16-1/2 inch spiral bevel gear used in the M915A16x4 tractor manufactured by AM General.  Five different preform designs were tried using lead as the model material. These tests were conducted at Battelle's Columbus Laboratories using a 700 ton hydraulic press. A special induction heating system was designed and fabricated for heating the preforms. The tool design was changed to have the teeth on the upper die to ensure proper flow and filling. Machine settings for the electrode were calculated using the computer program SPBEVL and graphite electrodes were machined on a Gleason No. 28 generator.					
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Gears were forged at Eaton's Marion, Ohio plant on an 8000-ton mechanical press. About 30 forgings were produced. The dimensions were checked on a computer-controlled coordinate measure machine. The measurements showed that the net forged gear tooth is an excellent reproduction of the master gear tooth form.

## PREFACE

This report covers the work performed under Phase III of Contract No. DAAK30-79-C-0071 from 30 Aug 1982 to 31 July 1985. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Army. This contract with Battelle Columbus Laboratories, Columbus, Ohio, was initiated under the Manufacturing Methods and Technology Project "Computer-Aided Design and Manufacturing (CAD/CAM) Techniques for Optimum Preform and Finish-Forging of Spiral Bevel Gears." It was conducted at the direction of Mr. Donald Ostberg of the Metals and Welding Subfunction (AMSTA-RCKM) of the U.S. Army Tank-Automotive Command (TACOM), Warren, Michigan. Battelle's Columbus Laboratories was the prime contractor on this program with Eaton Corporation of Cleveland, Ohio, as a subcontractor.

At Battelle, Dr. Taylan Altan was the Program Manager and Drs. P. S. Raghupathi and Aly Badawy were principal investigators. Other Battelle staff, namely Messers David Kuhlmann and Willis Sunderland, also contributed to the program as required.

At Eaton, the principal investigator and the project engineers were Messers. A. M. Sabroff, J. R. Douglas, and G. Horvat respectively. Other Eaton staff, namely Messers. G. Vollmer, R. Hoffman, T. Johnston, R. Fritsch, W. Litzenberg, contributed to the program.

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## 1.0. INTRODUCTION

In industrial practice, attempts are continuously made to introduce improved manufacturing methods to reduce production and life cycle costs. Close tolerance forging of spiral bevel gears, requiring only a single or no-finish machining operation, offers considerable advantages over machining because of a) the reduction in materials losses and machining costs, and b) the increase in fatigue life of gears up to 30 percent.

With the evolution of hard-finishing technology, namely the method to finish the gear teeth surfaces in the hardened condition by either using a grinding or fine-machining process, the precision forging technology for gears to rough finish tolerances has been introduced.

Currently, a few companies produce spiral bevel gears to near-net tolerances by precision forging. However, the development of the process for each gear design requires trial and error. Thus, applying computer techniques to the design and manufacture (Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM)) of the gear forging dies represents an attractive alternative.

In the program completed at Battelle, computer-aided methods were developed for gear forging die design and manufacture. The program was conducted in three phases. In Phase I (Reference 1) of the project, a computer program called SPBEVL was developed using methods based on finite element, metal forming, and heat transfer analysis. In Phase II, the results of the computer-aided techniques developed in Phase I of the program were evaluated for a given spiral bevel gear/pinion set by designing and manufacturing the forging dies. This phase was successful in forging gears with net and near-net tooth surfaces on a prototype basis. In the final phase, the task of forging a very large gear used in commercial applications was undertaken. The trials of forging the gears to near-net tolerances using dies designed by SPBEVL were successfully completed and a prototype lot of 10 gear sets was supplied to the U. S. Army. This report summarizes the work conducted in the last phase of the project.

It is expected that the techniques demonstrated by this project will be used in the near future for manufacturing, on a production basis, spiral bevel gears with near-net tolerances on the teeth. The matching pinions will still be manufactured by conventional methods. Thus, by eliminating the rough tooth-cutting process for the gear, considerable savings can be expected. With additional efforts to include the distortion effects due to cooling from the forging heat in the computer-aided design of dies, gears can be produced to net tolerances (no machining on functional surfaces) on a production basis.

The existing data on forged straight bevel gears indicate that forged bevel gears are superior in terms of fatigue life and load-carrying capability. A similar improvement in performance can also be expected from forged spiral bevel gears.

## 2.0. PURPOSE AND OBJECTIVES

The overall objective of the program was to develop a general purpose CAD/CAM technique for producing precision forging dies for families of spiral bevel gears. Thus, the specific objectives of the program were to

- Optimize the design and manufacture of dies used in precision gear forging using CAD/CAM techniques;
- Reduce the cost of die and process development for precision forging of spiral bevel gears of different sizes by CAD/CAM techniques; and
- Make the CAD/CAM system sufficiently flexible so that a) it can be used for a family of bevel gears, and b) it can easily be introduced into production forge shops.

In Phase I of the project, the CAD program (SPBEVL) for designing spiral bevel gear forging dies was completed. The integration of the CAD and CAM processes into one system was achieved in Phase II of the project by manufacturing the forging dies for a selected gear and forging prototype gears to net and near-net tolerances. Phase III of the project investigated the precision forging of a very large commercially used spiral bevel gear to near-net tolerances.

## 3.0. BACKGROUND

All significant precision gear manufacturing methods and technology programs conducted in the U.S. have been sponsored by the U.S. Army. A brief summary of these programs was given in the Phase I report (Reference 1). Two major studies, one using a High Energy Rate Forging (HERF) machine and the other using a mechanical forging press, were conducted for precision forging of spiral bevel gears. Even though projects developed valuable detailed information, these approaches were not implemented in production. However, some companies in Japan and West Germany forge spiral bevel gears to net and near-net tolerances on a production basis.

Precision warm or hot-forging of straight bevel gears is a well accepted production method in the U.S. and abroad. In a typical forging operation, slugs are sawn from peeled, machined or centerless-ground hot rolled bar to close weight tolerances. They are heated by induction under neutral atmosphere 900°F to 2000°F (480°C to 1200°C). In some cases, the slugs may be coated with lubricant prior to heating. Forging is usually done in two operations: blocker and finisher.

The forged parts are cooled slowly and uniformly either under airflow or by placing the tooth side of the gears into a sand-graphite mixture. Forging flash and the back side of the gears are machined by holding the gear on the pitch line in special fixtures. A negative of the tooth form locates the component insuring a correct relationship between machined faces, center holes, and the forged teeth. Machined gears are inspected using special fixtures. If extreme accuracy is required, a cold coining operation on a hydraulic press is performed on the surface of the teeth. The key to successful precision forging is the design and manufacture of the dies to precise dimensions. Corrections in the gear teeth impressions in the die must be made to account for shrinkage, thermal, and elastic deflections. The die cavity is usually made by electrodischarge machining (EDM) using an electrode with the corrected dimensions.

The extension of the above technology to the precision forging of spiral bevel gears is not, however, straightforward. The spiral tooth shape requires much more careful die correction and die engineering than that necessary for straight bevel gears.

#### 4.0. PROGRAM HIGHLIGHTS

##### 4.1. Application of CAD/CAM to Forging

In recent years, CAD/CAM techniques have been applied to die design and manufacture for forging a) rib-web type aircraft structural parts (Reference 2), b) track shoes for military vehicles (Reference 3), and c) precision turbine and compressor blades (Reference 4). The experience gained in all these applications indicates that a certain overall methodology is necessary for the CAD/CAM of dies for precision and/or net and near net-shape forging. The necessary input required for applying CAD/CAM techniques in the design of dies for precision forging are:

- geometric description of the forging,
- data on billet material under forging conditions (billet and die temperatures, and rate and amount of deformation),

- friction coefficient to quantify the friction shear stress at material and die interface, and
- forging conditions, i.e., temperature, deformation rates, die lubricants, method of heating the billets, and suggested number of forging operations.

With these input data, a preliminary design of the finish forging die can be made. The loads necessary to finish forge the part and the temperatures in the finish forging die are then calculated. The temperature calculations take into account the heat generated due to deformation and friction, and the heat transfer during the contact between the hot forging and the cooler dies. Thus, the elastic die deflections due to temperatures and loads can be estimated. The finish die geometry can therefore be corrected accordingly. The above procedure was also used in the current project.

#### 4.2. Program Outline

The program was conducted in three phases:

Phase I - CAD of Forging Dies. The results of the work performed in this phase was summarized in a final report (Reference 1).

Phase II - CAM of forging dies and demonstration of the effectiveness of CAD/CAM by forging 20 spiral bevel gear sets. The results of this phase were summarized in a report (Reference 5).

Phase III - Application of CAD/CAM techniques to the actual production of spiral bevel gears by forging. This report describes the work accomplished in this phase.

### 5.0. PROGRAM APPROACH

#### 5.1. Summary of Phase I Work

All of the Phase I work was conducted at Battelle with some input from Eaton Corporation (subcontractor) and Mr. L. Baxter (consultant to the program). Phase I consisted of three major tasks; a brief description of these follows (for detailed information, please refer to Reference 1).

5.1.1. Task 1. Transformation of Dimensional Data into Computer-Compatible Digital Data. The kinematics of the gear machines (generators) employed to cut the spiral bevel gears were used to develop the gear tooth geometry. Figure 5-1 and Table 5-1 explain the algorithm used to generate the geometry of the spiral bevel gears.



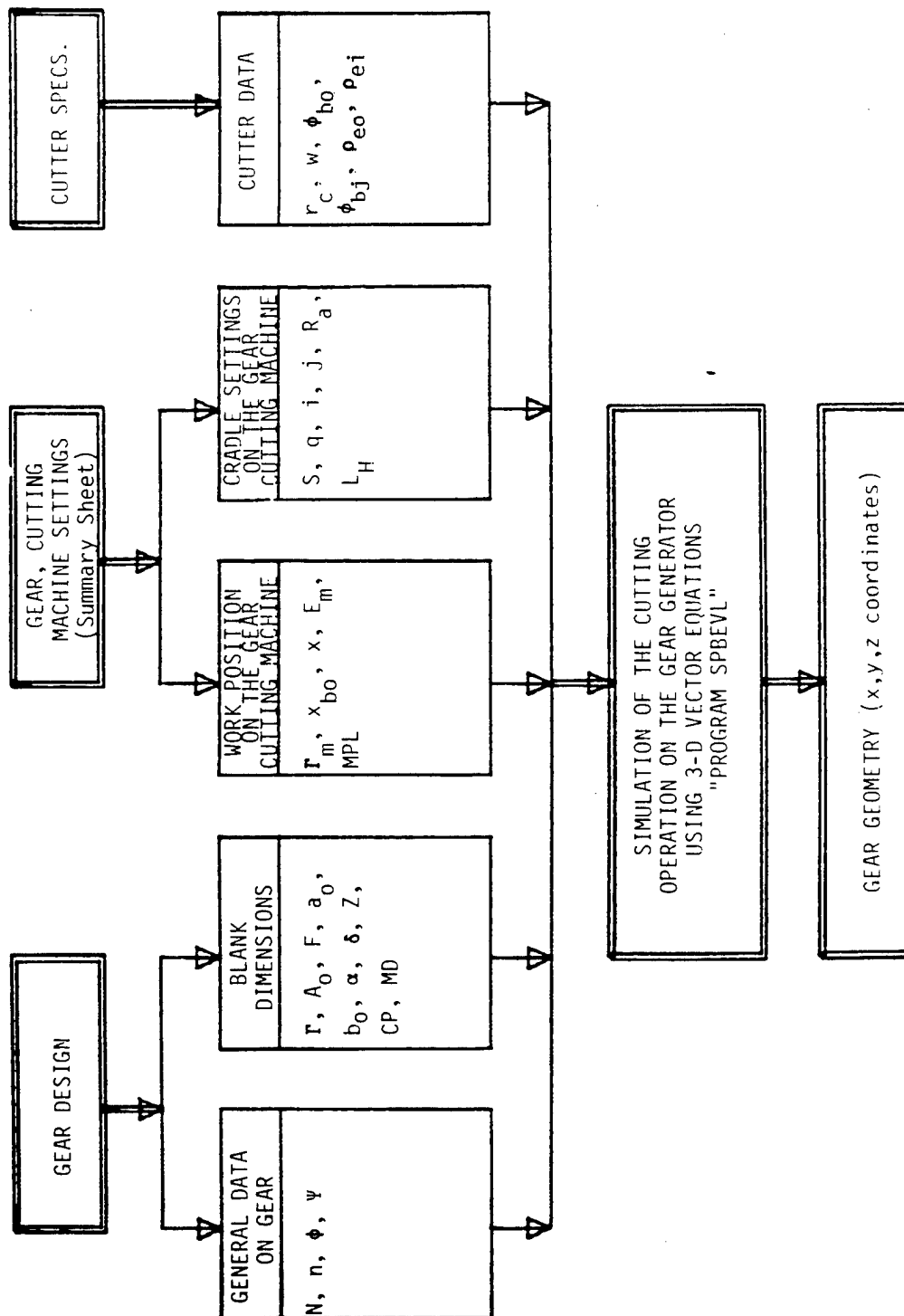


Figure 5-1. Input Data Necessary for Generating Spiral Bevel Gear Tooth Profile  
(Explanation of these Data is Summarized in Table 5-1.)

The motions of the gear cutting machine (only machines made by the Gleason Works, Rochester, New York were considered in this project) were simulated for the given machine settings and for the given blank and cutter dimensions (Reference 6).

5.1.2. Task 2. Computer Aided Design of Forging Dies. During the forging process, both the forged gear and the dies experience dimensional variations due to elastic deflections, bulk shrinkage, and temperature differentials. To obtain the desirable accuracy in the forged gears, the above mentioned variables should be estimated and the die geometry should be corrected accordingly. This was accomplished by the following.

- Calculating the stress distribution and forging load using slab method (Reference 7), and the finite element method (Reference 8);
- Estimating the elastic die deflections due to mechanical loading;
- Calculating the temperature distributions;
- Estimating the bulk shrinkage due to shrink- or press-fit assembly; and
- Modifying the gear tooth geometry.

These detailed computations demonstrated that the largest component of the corrections necessary was due to temperature effects.

For machining the electrodes with the appropriate corrections, the same gear cutting machine was selected to be used, as Numerical Control (NC) machining was found to be uneconomical. Using average corrections for temperature, elastic deflections, and shrink-fitting, the new machine settings, cutter dimensions, and blank dimensions were calculated.

5.1.3. Task 3. Development of the Interactive CAD System. A computer program called SPBEVL was developed to include all the mathematical analysis developed in Tasks 1 and 2. SPBEVL, an interactive computer program was used to display the results on a graphics terminal. Some examples of various displays are shown in Figures 5-2 through 5-5. By specifying the forging conditions, material properties, and die assembly specifications, the corrected tooth geometry could be displayed and the new machine settings, blank dimensions and cutter dimensions to machine the electrodes with the corrected geometry could be computed.

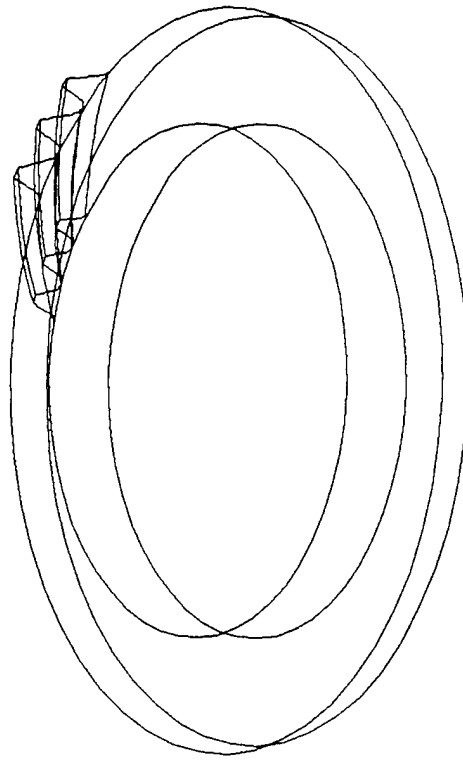


Figure 5-2. Isometric View of a Spiral Bevel Ring Gear as Displayed on the Graphic Display Terminal

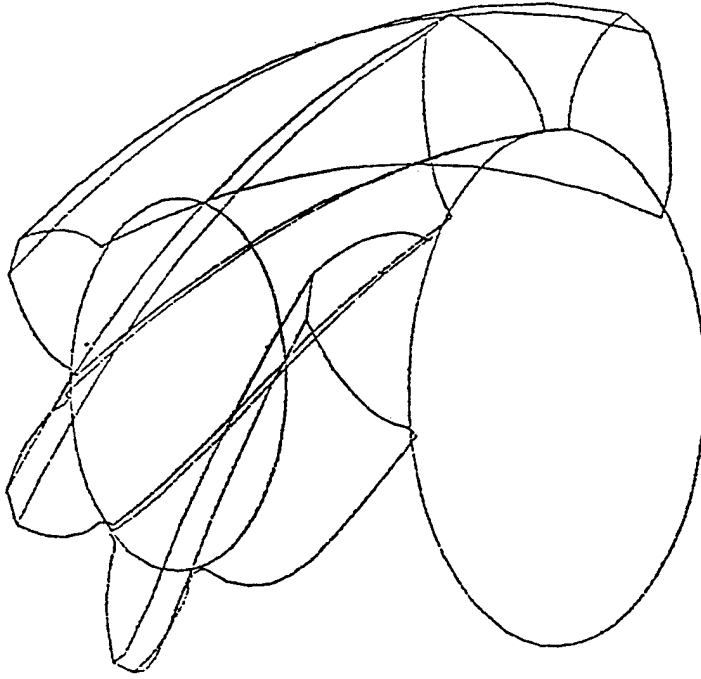


Figure 5-3. Isometric View of a Spiral Bevel Pinion as Displayed on the Graphic Display Terminal

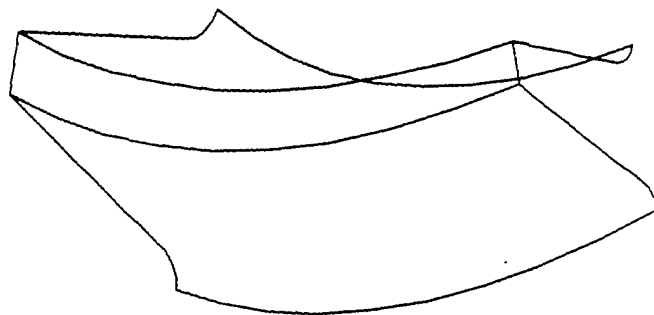


Figure 5-4. Tooth Form as Displayed on the Graphic Display Terminal

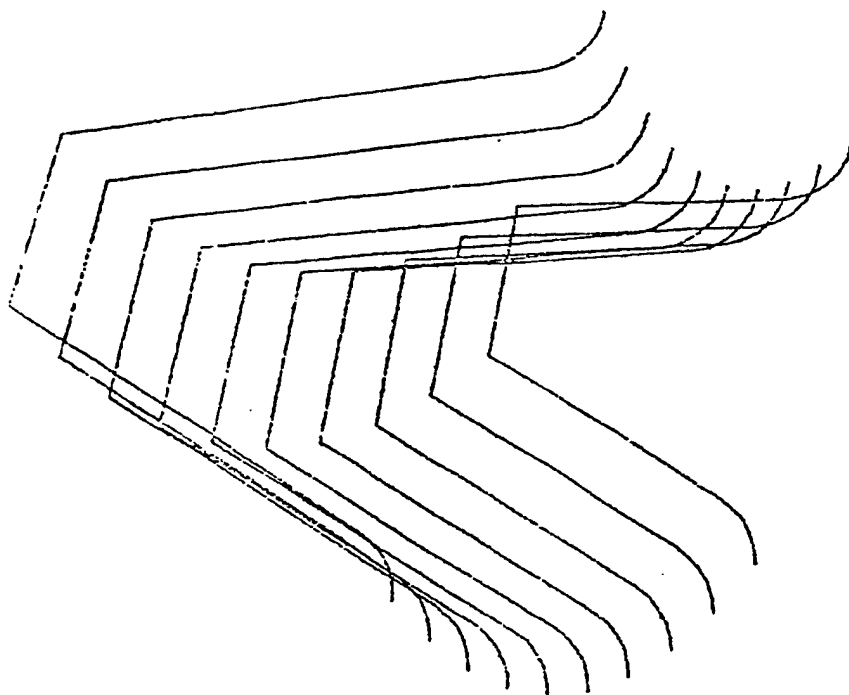


Figure 5-5. Cross Sections of a Tooth as Displayed on the Graphic Display Terminal

## 5.2. Summary of Phase II Work

Most of the work under this task was performed jointly by both Battelle and Eaton. A brief description of the five major tasks carried out in Phase II of the project follows (for more details, please refer to References 5,9, and 10).

5.2.1. Task 1. Preform Design and Manufacture. Two different preforms were designed. These were made by machining upset pancakes from billet stock. (The conventional method of making the blocker or preform by forming methods was not used due to the developmental nature of the project.)

5.2.2. Task 2. Tool Design. A schematic of the forging tooling used is shown in Figure 5-6. The flashing was toward the inner diameter. Inside the flash area was a gutter for excess material to flow into.

5.2.3. Task 3. Manufacture of Forging Dies. Hot work steel H-11 was used as the die material for the near-net forging trials and H-13 for the net forging trials. The billet material was 8620 steel. The EDM electrodes were machined on a conventional gear cutting machine, using machine settings calculated from the computer program SPBEVL.

5.2.4. Task 4. Forging Trials. The trials were conducted at Eaton Corporation's forging division in Marion, Ohio. A 3,000-ton mechanical forging press, manufactured by National Machinery Company, Tiffin, Ohio, was used to perform the trials. Three series of forging trials were conducted. During the first trials, the technological aspects of the forging procedure such as heating, lubrication, billet temperature, and cooling were established. During the second forging trials, 20 gears were forged with a 0.007 inch (0.178 mm) machining allowance on both tooth surfaces. These near-net forged gears were subsequently finish-machined with a single machining operation. The third series of trials was conducted to forge 20 gears with net tooth dimensions. Both the trials for near-net and net forged gears were successful.

5.2.5. Task 5. Finishing and Dimensional Checking of Forged Gears. A special nesting device was made to locate the forged gears on their pitch line to finish-machine the back surfaces (Figure 5-7). The contact pattern obtained after finish-machining was excellent.

The gears were also checked for their dimensional accuracy on a computer-controlled coordinate measuring machine (manufactured by Zeiss Corporation in West Germany) in the Eaton Axle Gear Laboratory. The relative error as compared with a "master gear" tooth produced by conventional cutting using a Gleason generator was zero at the center of the profile and showed a maximum variation of 0.003 inch (0.076 mm). This difference can be easily compensated for in the machining of the pinion.

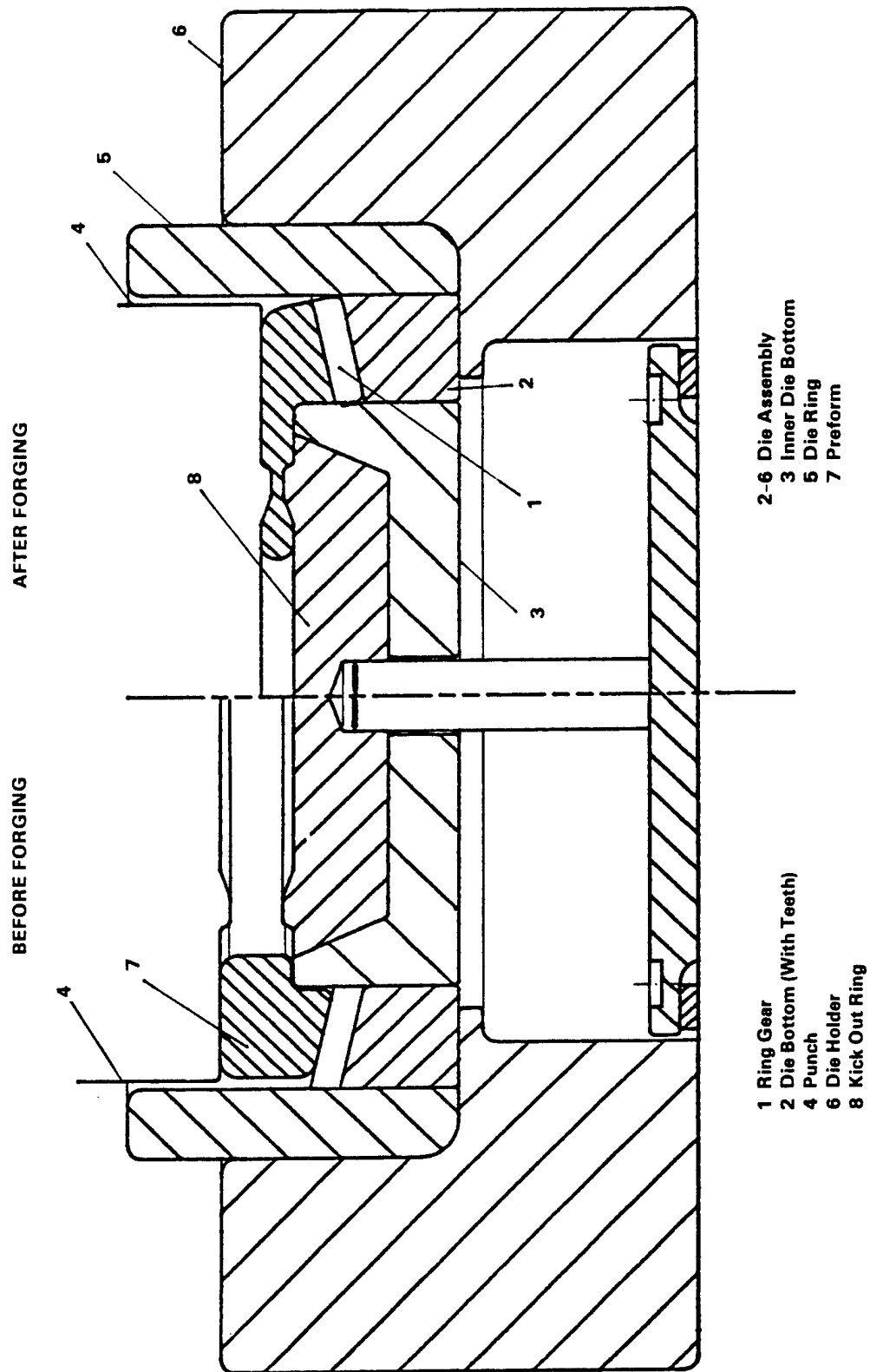


Figure 5-6. Schematic of the Forging Tooling

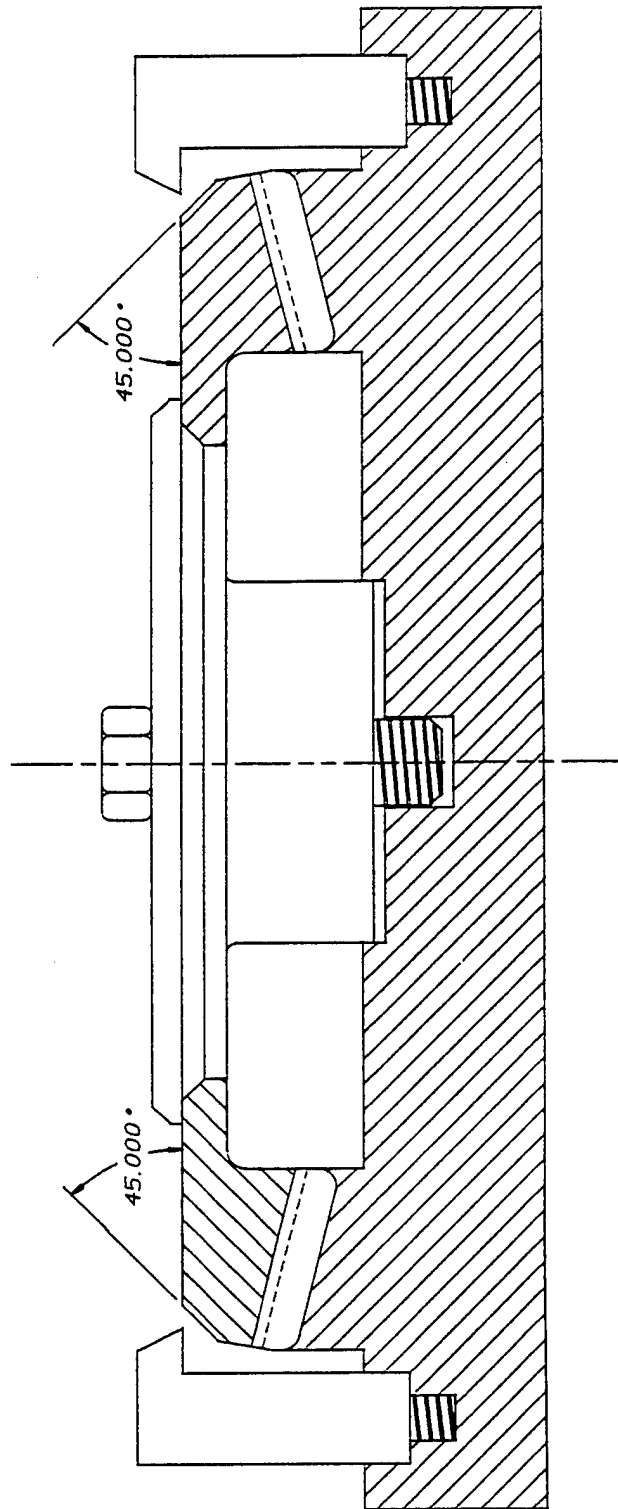


Figure 5-7. Clamping Arrangement of the Nest, Used For Machining the Back Side of Forged Gears

### 5.3. Program Approach for Phase III

5.3.1. Selection of the Gears. For Phase III it was decided that the results of Phases I and II should be demonstrated by implementing the process on a truck size ring gear presently being used on a military vehicle. For this purpose the gear set in Eaton's axle no. DS401P was selected. This axle is used in the M915A1 6x4 tractor manufactured by AM General. A brief description of the tractor and its applications is shown in Figure 5-8.

The gear used in this tractor is a 16-1/2 inch spiral bevel ring gear. Major features of the gear are summarized in the engineering drawing shown in Figure 5-9.

The gear was to be forged to a near-net configuration similar to that demonstrated in Phase II. This forging was then to be further processed to a fully machined and heat-treated gear. The gear finally produced in this phase will then be identical to the gear in the M915A1 tractor drive axle.

5.3.2. Forging Analysis Using SPBEVL. The spiral bevel gear program SPBEVL, which was developed in Phase I of this project, was used to predict the machine settings required to machine the EDM electrodes to cut the forging dies. The input and output of SPBEVL are shown in Figures 5-10 and 5-11 respectively.

The output of SPBEVL gives the new machine settings including the corrections due to deflections resulting from: loading, temperature differentials between the die and workpiece, and bulk shrinkage. Note that die temperature was kept at 176°C, the billet temperature was kept at 1150°C and the machining allowance was 0.01 inches.

As shown in Figures 5-10 and 5-11, the Gleason's 28 gearcutting machine (generator) was used to machine the graphite electrode.

### 5.3.3. Process Design.

5.3.3.1. Preform design. One of the most important aspects of the forging process is the proper design for preforming (or blocking) operations. The following three features were considered while designing the preform to be used in this program for forging spiral bevel gears.

First, it was necessary to design a preform that would assure defect-free metal flow and adequate die filling. Adequate metal distribution is necessary in the blocker design to avoid forging defects, such as cold shuts and folds. The preform was designed as a solid ring (no teeth) with the outer dimensions as close as possible to the outer dimensions of the finished gear. This minimizes the amount of material to be moved during forging and in turn, enhances die filling.





**14 TON LINE HAUL TRACTOR  
ENGINEERED SPECIFICALLY  
FOR THE MILITARY.**

**AM General**  
World Class Capability

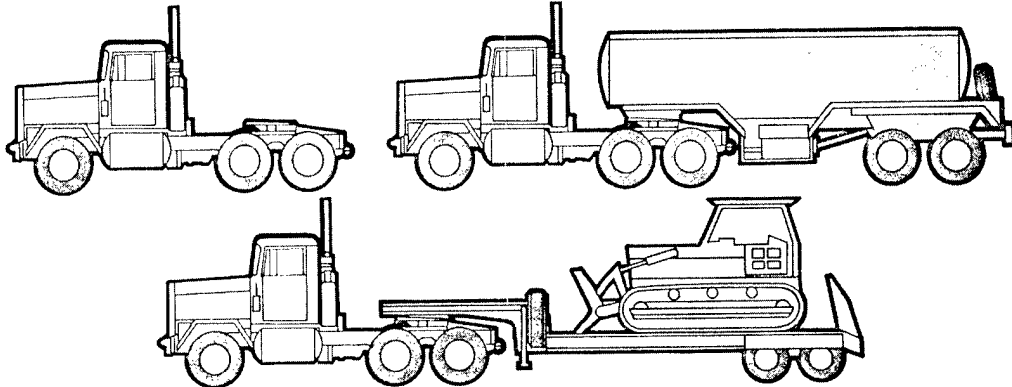
Figure 5-8. The M915A1 Line Haul Tractor, Made by AM General,  
That Uses the Spiral Bevel Gears Made in this  
Program

The M915A1 6x4 line haul tractor is a heavy-duty truck designed for hauling bulk cargo over highways and secondary roads. The truck tractor is compatible with semi-trailers of all configurations including flatbed, stake, low bed and tankers for fuel and water. This truck can haul a payload of 28,400 lbs. It comes equipped with a pintle hook which can tow 50,000 lbs. The Gross Combination Weight Rating is 105,000 lbs.

The truck was developed for the U.S. Army using heavy-duty components proven in the truck industry and readily available for worldwide service and support. Major components in the M915A1 include a 400 horsepower

diesel engine, automatic transmission, heavy-duty axles and air actuated brakes. Standard military features include front tow hooks, blackout lights, portable lighting equipment and tie-down provisions for rail and air transport.

All vehicle systems in the M915A1 reflect the high standards of quality and reliability for which AM General military trucks are known throughout the world. AM General trucks are backed up by the most thorough and respected Integrated Logistics Support System. This assures all users of top quality spare parts, technical service engineering assistance, training, manuals and publications.



SPECIFICATIONS			
<b>DIMENSIONAL DATA:</b>		Maximum Drawbar Pull.....	20,010 lbs.
Overall Length.....	255.5 in.	<b>ENGINE:</b>	
Overall Width.....	96.0 in.	Diesel 6 Cylinder, 4 Cycle.	
Height.....	117.5 in.	Turbo Charged.....	Cummins NTC 400
Wheelbase.....	167.0 in.	Horsepower—Gross Torque 1,150 lbs. ft. @ 1,500 RPM	
Tread Width.....		Fuel Capacity.....	118 gallons
Front.....	78.4 in.	<b>TRANSMISSION:</b>	
Rear.....	71.5 in.	Automatic, 5-Speed.....	Detroit Diesel Allison HT 754CR
Fording Depth.....	24.0 in.	<b>AXLES:</b>	
<b>PERFORMANCE:</b>		Front.....	Eaton—EFA—13F3
Maximum Speed.....		Rear Tandem.....	Eaton—DS 401P
Full Load Governed RPM.....	57 mph	<b>SUSPENSION:</b>	
Speed on 3% Grade.....	28 mph	Front.....	Pin and Shackle Leaf Spring
Maximum Gradeability.....	18.4%	Rear Tandem.....	Hendrickson RTE 380
Minimum Sustained Speed @ 1,200 RPM.....	2.0 mph	<b>WHEELS:</b>	
		Single Piece.....	Firestone Model 27404, 20x8.25
		<b>TIRES:</b>	
		Steel Belted.....	Goodyear 11.R22.5 LR "G" Tubeless Radial Ply
		<b>STEERING:</b>	
		Gear.....	Ross HFB 64
		Pump.....	Gear Driven—Eaton B165R
		<b>BRAKES:</b>	
		Service.....	Eaton—Air Actuated
		Front Axle.....	Type 16 1/2 x 5 "S" Cam
		Rear Tandem.....	Type 16 1/2 x 7 "S" Cam
		Parking.....	Anchor Lok Model 3030
		<b>PINTLE:</b>	
		Type.....	Holland No. 760
		Rated Capacity.....	25 ton

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AMG 10 B1

Figure 5-8. The M915A1 Line Haul Tractor, Made by AM General, That Uses the Spiral Bevel Gears Made in this Program (Continued)

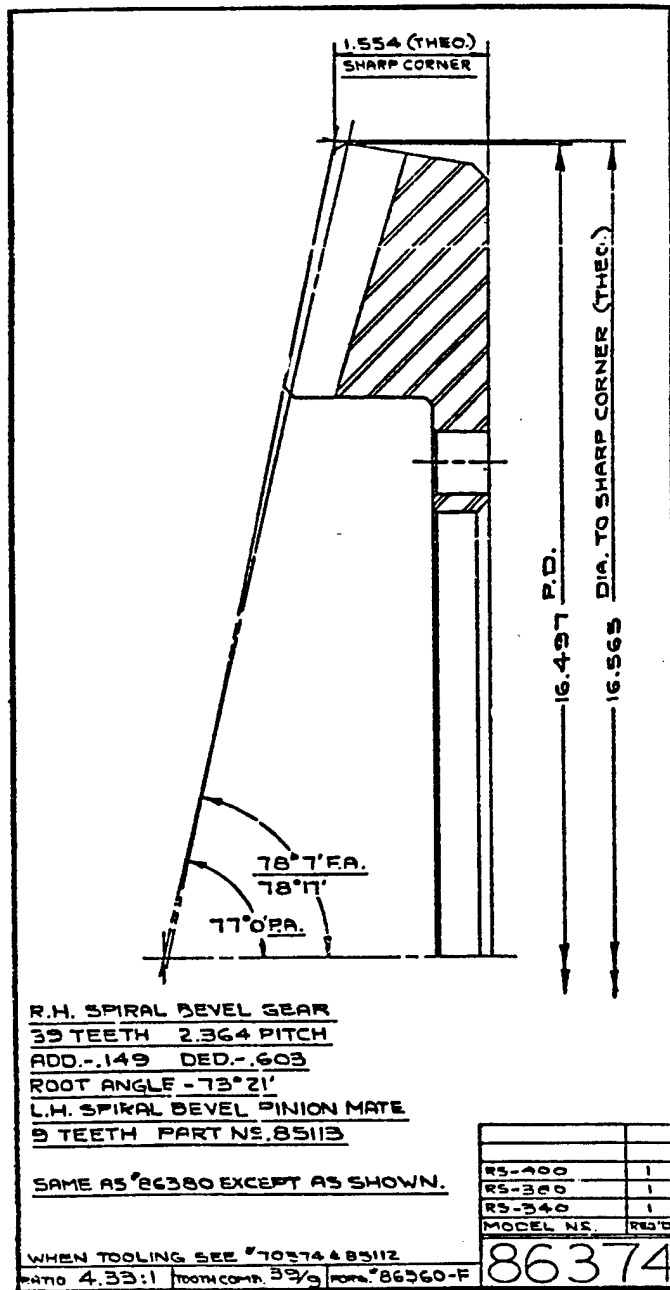


Figure 5-9. Engineering Drawing For the Spiral Bevel Gear Forged in This Program (Eaton Part No. 86374)

20-DEC-85

09:04:11

FOR THE GEAR

\*\*\* BLANK DIMENSIONS \*\*\*

NUMBER OF TEETH . . . . .	=	39
PRESSURE ANGLE. . . . .	=	200 0M
SPIRAL ANGLE. . . . .	=	350 0M
FACE ANGLE. . . . .	=	780 3M
PITCH ANGLE . . . . .	=	770 0M
DEDENDUM ANGLE . . . . .	=	30 44M
OUTER CONE DISTANCE . .	=	8.467 INCH
FACE WIDTH. . . . .	=	2.625 INCH
ADDENDUM. . . . .	=	0.148 INCH
DEDUNDUM. . . . .	=	0.604 INCH
DISTANCE BETWEEN CROSSING POINT AND CONE APEX .	=	0.000 INCH
MOUNTING DISTANCE . . .	=	3.312 INCH

20-DEC-85

09:04:11

FOR THE GEAR

\*\*\* CUTTER SPECIFICATIONS \*\*\*

CUTTER DIAMETER . . . . .	=	12.000 INCH
POINT WIDTH . . . . .	=	0.250 INCH
OUTSIDE BLADE ANGLE . .	=	200 0M
INSIDE BLADE ANGLE. . .	=	200 0M
OUTSIDE BLADE EDGE RADIUS=	=	0.130 INCH
INSIDE BLADE EDGE RADIUS =	=	0.130 INCH

Figure 5-10. Input and Output Data For Designing the Dies  
For Forging the Spiral Bevel Gear With a  
Machining Allowance of 0.010 in.

FOR THE GEAR

\*\*\* WORK AND CRADLE SETTINGS \*\*\*

MACHINE ROOT ANGLE. . . = 74D 24M  
MACHINE CENTER TO BACK = MD -0.214 INCH  
SLIDING BASE. . . . . = 0.000 INCH  
BLANK OFFSET. . . . . = 0.000 INCH  
ECCENTRIC ANGLE . . . . = 53D 53M  
CRADLE ANGLE. . . . . = 343D 51M  
RATIO ROLL GEARS. . . . =  
LINEAR MOTION OF CRADLE =  
ABOUT ITS AXIS FOR 20 D= 0.000 INCH

FOR THE GEAR

\*\*\* TOOTH AND PROCESS SPECIFICATIONS \*\*\*

MEAN WHOLE TOOTH DEPTH. . = 0.642 INCH  
MEAN CHORDAL THICKNESS. . = 0.291 INCH  
MEAN CHORDAL ADDENDUM . . = 0.124 INCH  
DIAMETRAL PITCH . . . . . = 2.364 INCH  
BILLET TEMPERATURE (C). . = 1150.000  
DIE TEMPERATURE (C) . . . = 176.600

FOR THE GEAR

\*\*\* SHRINK FIT SPECIFICATIONS \*\*\*

INNER DIAMETER OF ASSEMBLY = 16.567 INCH  
ELASTIC MODULUS OF INSERT (KSI) = 30000.000  
ELASTIC MODULUS OF OUTER RING (KSI)= 30000.000  
POISSON RATIO OF INSERT = 0.300  
POISSON RATIO OF OUTER RING = 0.300  
YIELD STRENGTH OF INSERT (KSI) = 170.000  
YIELD STRENGTH OF OUTER RING (KSI) = 130.000

Figure 5-10. Input and Output Data For Designing the Dies  
For Forging the Spiral Bevel Gear With A  
Machining Allowance of 0.010 in. (Continued)

NEW MACHINE SETTING VALUES ARE CALCULATED  
FOR SPREAD BLADE CUTTING ON  
GLEASON GENERATORS NO.26 AND NO.28

FOR THE GEAR

\*\*\* NEW BLANK DIMENSIONS \*\*\*

NUMBER OF TEETH . . . . .	=	39
PRESSURE ANGLE. . . . .	=	200 0M
SPIRAL ANGLE. . . . .	=	350 0M
FACE ANGLE. . . . .	=	780 3M32S
PITCH ANGLE . . . . .	=	770 0M34S
DEDENDUM ANGLE . . . . .	=	30 43M51S
OUTER CONE DISTANCE . .	=	8.661INCH
FACE WIDTH . . . . .	=	2.685INCH
ADDENDUM. . . . .	=	0.151INCH
DEDUNDUM. . . . .	=	0.617INCH
DISTANCE BETWEEN CROSSING		
POINT AND CONE APEX .	=	0.000INCH
MOUNTING DISTANCE . . .	=	3.385INCH

FOR THE GEAR

\*\*\* NEW CUTTER SPECIFICATIONS \*\*\*

CUTTER DIAMETER . . . . .	=	12.275INCH
POINT WIDTH . . . . .	=	0.243INCH
OUTSIDE BLADE ANGLE. . .	=	200 1M54S
INSIDE BLADE ANGLE . . .	=	190 59M32S
OUTSIDE BLADE EDGE RADIUS	=	0.133INCH
INSIDE BLADE EDGE RADIUS	=	0.133INCH

FOR THE GEAR

\*\*\* CHANGED WORK AND CRADLE SETTINGS \*\*\*

MACHINE ROOT ANGLE. . .	=	740 24M40S
MACHINE CENTER TO BACK.	=	MD -0.219 INCH
SLIDING BASE. . . . .	=	WITH0.010 INCH
ECCENTRIC ANGLE . . . . .	=	550 13M13S
CRADLE ANGLE	=	3440 31M 6S

Figure 5-11. Output Data From SPBEVL in the Form of  
Machine Settings For Cutting Electrodes  
For EDMing the Forging Dies

Second, it is important to minimize material lost to flash. In steel forgings, approximately half of the cost of forging consists of material costs. On the average, 30 percent of the incoming forging stock is lost in the form of flash. Thus, approximately 15 percent of the forging costs are in the flash material of relatively little recoverable scrap value. The design of the blocker shape used in this program produced no flash on the outside of the forging and very little flash on the inside. This was due to the fact that the volume (or weight) of the preform was slightly larger than the volume of the finished gear, and the proper material distribution throughout the preform volume was achieved.

Finally, it is important that the preform be designed for ease of centering in the finish die. The need for this is obvious since a poorly centered preform will cause uneven flow and unacceptable fill in the forgings. The requirement for a carefully centered preform is especially important when the process is designed to be flashless.

Modeling trials with lead were conducted in this program to determine the best preform for forging the spiral bevel ring gear. These efforts are described later in this report.

The preform shape, finally selected for use in the forging trials, is shown in Figure 5-12.

5.3.3.2. Tooling Design. The tooling design used in this phase of the program is shown in Figure 5-13. This design is similar to the tooling used in Phase II except that the punch and die arrangement are inverted.

The die assembly (upper tooling) consists of an insert (containing the tooth form) surrounded by a support ring. The support ring provides reinforcement support to the insert and forms the outer diameter of the gear during forging. Inside of the insert is the inner die and the center kick out. The inner die forms the inner diameter of the forging and the forging and the center kick out presses against the forging flange to remove the forging from the die. The kick out is activated by a mechanical mechanism in the press that is engaged during the upstroke of the press.

The lower tooling is a punch type arrangement on which the preform rests prior to forging. The term "punch" is normally reserved for the moving tooling (or upper tooling) in a typical forging die arrangement. In this case, however, the tooling was inverted from the arrangement that is normally used. Thus, the "punch" was on the lower bolster of the press and, therefore, was the stationary portion of the tooling.

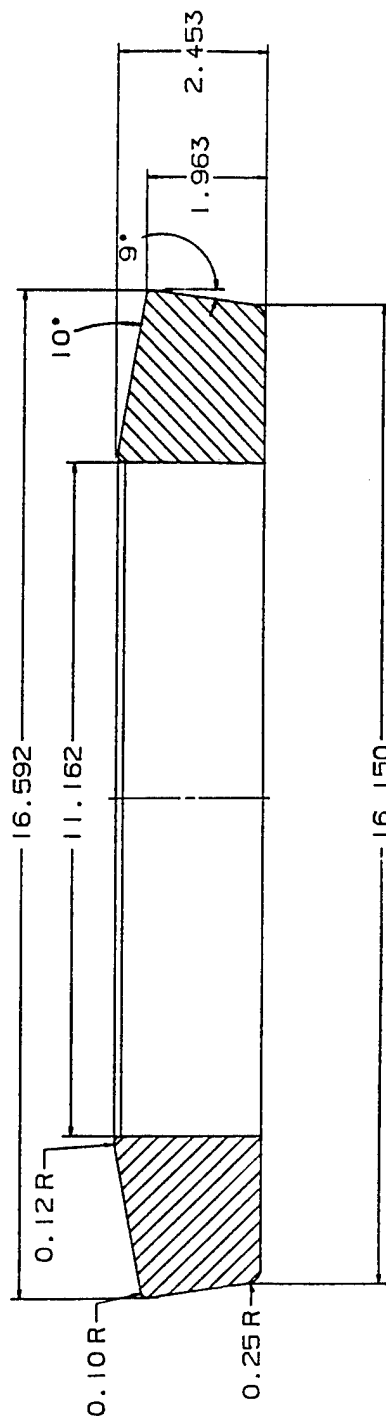


Figure 5-12. Preform Shape Used in This Program for Forging the Spiral Bevel Gears



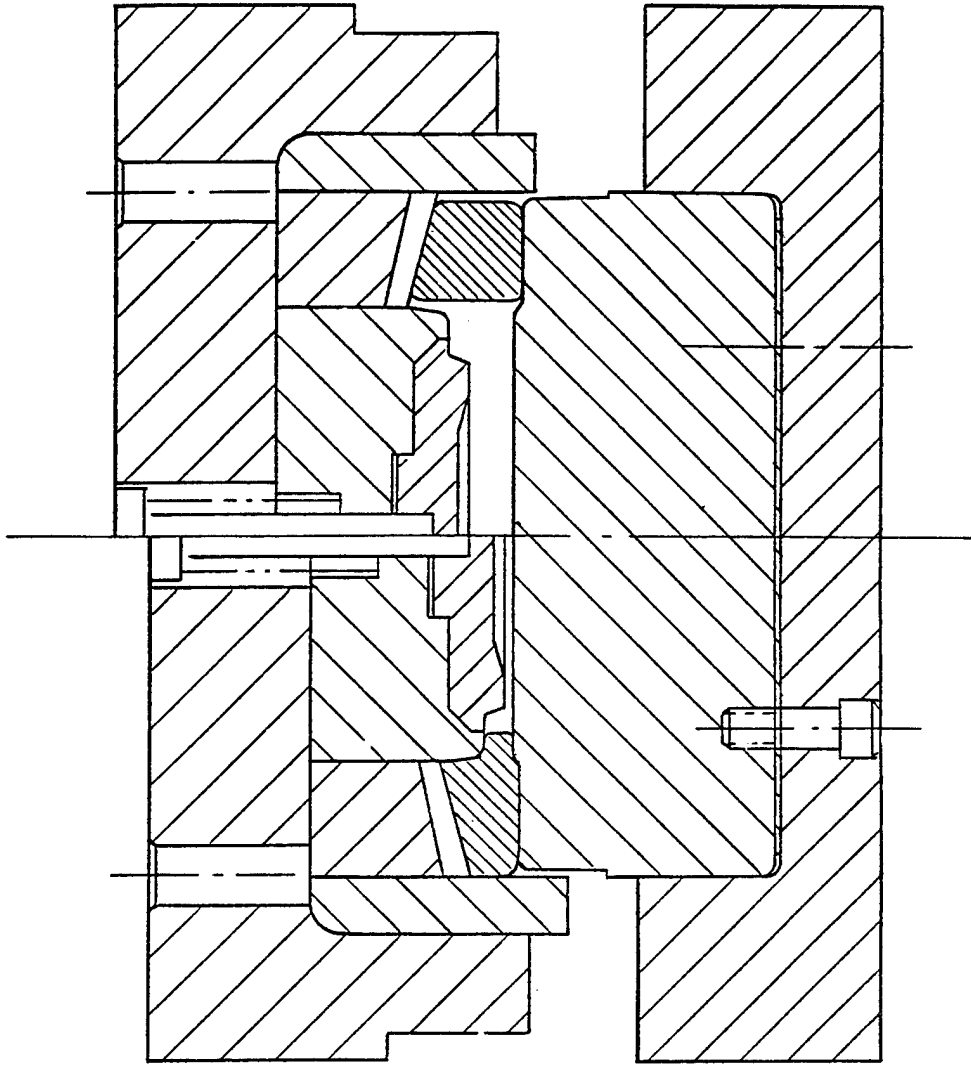


Figure 5-13. Schematic of the Forging Tooling

5.3.3.3. Process variables. The parameters for forging the spiral bevel gears were well established in Phase II of this program. Close tolerance forgings were made that could easily be processed into finish-machined spiral bevel ring gears. In this phase, only that large, heavy truck spiral bevel gears could be forged with near-net teeth under production conditions had to be demonstrated. Thus, the process variables for the final forging trials were as follows.

Forging Press	- 8000-ton National
Billet Temperature	- 2100F (1150C)
Die Temperature	- 300F (150C)
Billet Coating	- None
Die Lubricant	- Acheson Deltaforge 31
Billet Heating	- Induction heating with Nitrogen as a protective atmosphere
Billet Material	- AISI 8620 steel
Heating Time	- 8.0 minutes
Instrumentation	- Helms Load Monitor - Ircon Temperature Sensor
Cooling Method	- Sand and graphite mix

5.3.4. Modeling Trials with Lead. Five different preform designs were designed for possible use in this program and are shown in Figure 5-14. To test these preform configurations, it was decided to conduct physical modeling studies using lead samples. For simplicity, the forging tooling used in Phase II of this program was used for these modeling trials. The modeling studies were conducted at Battelle's Columbus Laboratories using a 700 ton hydraulic press.

The most successful of the five preform designs were Nos. 4 and 5. These preforms gave the best overall corner fill and seemed to require the least energy to fill the die. Preform shape No. 5 was ultimately selected as the shape to be used in the forging trials.

5.3.5. Design of the Heating System. The heating system used in this phase consisted of an induction work station, a ring-heating fixture, and an induction coil. The design used in the initial trials, shown in Figure 5-15 was supplied by I-Square R Company of Mentor, Ohio.

The work station consisted of an auto-transformer, high frequency capacitors, and a capacitor contactor. It also included a bus stud output, a closed drain, a pressure gauge, and door interlocks.

The ring-heating fixture consisted of a structural steel framework providing support for the induction coil, and a pneumatically operated ring support/lift mechanism. The lift mechanism was designed to raise and lower the ring via a pneumatic cylinder having push button control.

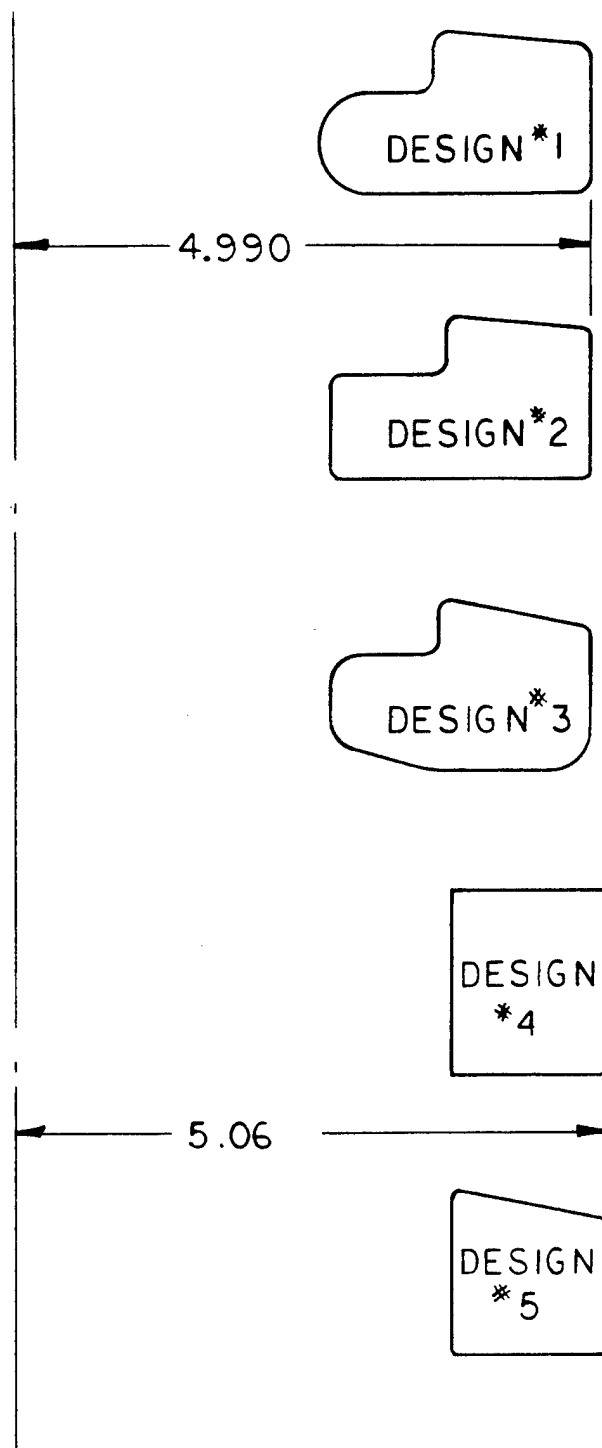


Figure 5-14. The Five Preform Shapes Tested in the Modeling Trials

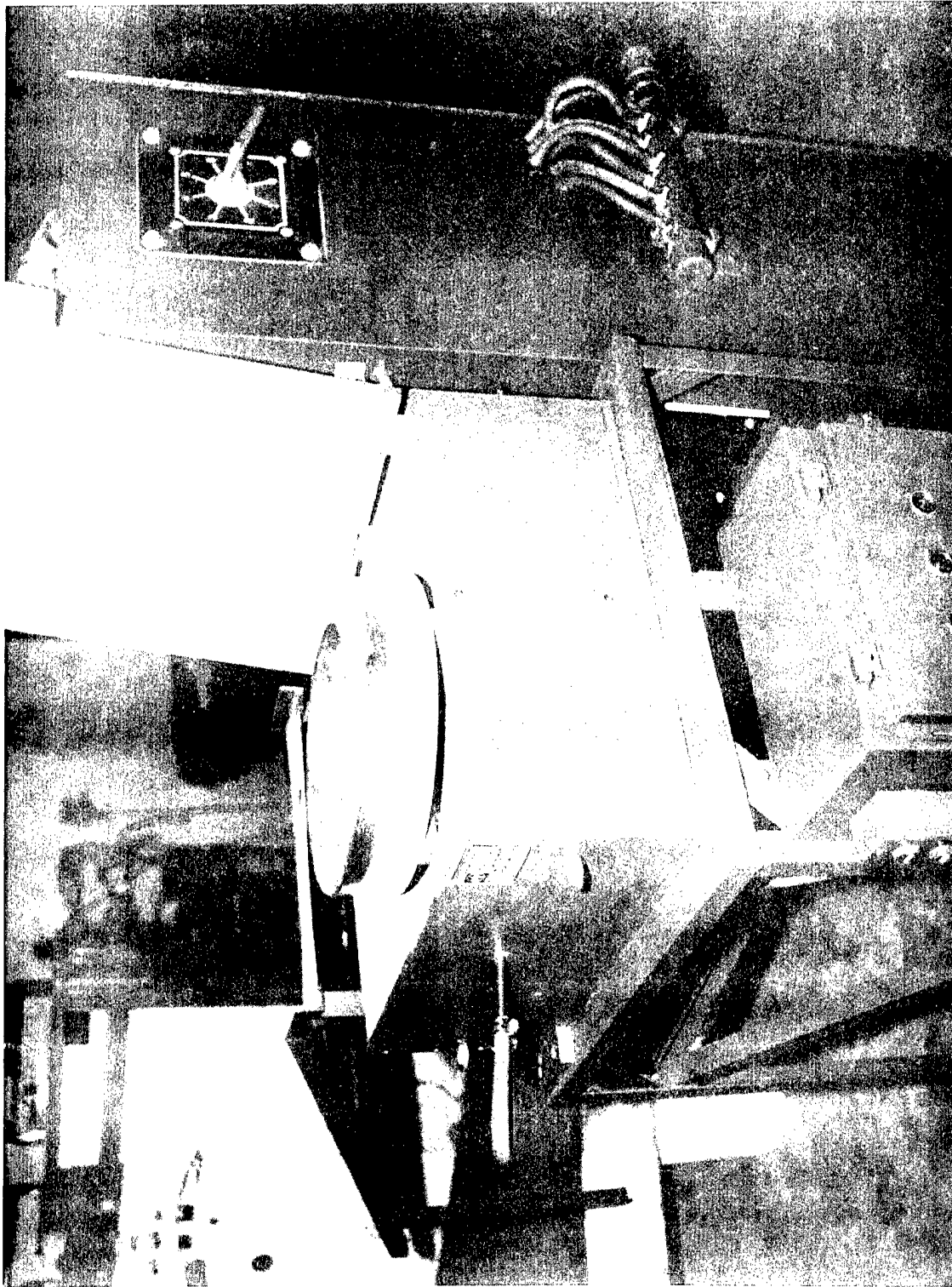


Figure 5-15. The Induction Heating Coil and Work Station  
Used in the Initial Forging Trials

The ring to be heated was loaded and unloaded manually. The fixture also included a time and buzzer for cycle control. After the ring was raised into the coil, the operator pressed a heat cycle start button. The duration of the heat cycle could be controlled by either the timer or by the operator.

The coil was designed specifically to heat the ring preform selected for this program. The coil turns were made of copper tubing and carefully insulated using varnish and fiberglass tape. The coil was cast in alumina refractory for insulation, strength, and protection. The coil was mounted on the ring-heating fixture above the ring support/lift mechanism.

5.3.6. Preparation of Electrodes. The EDM process is a well established process that can provide an impression of great precision in forging dies. However, the accuracy of the impression can be no better than that of the electrodes. Thus, the electrodes must be carefully prepared as a preliminary step to making precision forging dies.

There are usually two choices for electrode material -- brass and graphite. Brass electrodes are easily machined and produce a very fine surface finish that is desirable for forge tooling. The major drawback to brass is the wear ratio of electrode material removed compared to the die material removed, which is approximately one to one. Graphite electrodes, on the other hand, even though they machine with more difficulty, offer many advantages. The most significant advantage is that the wear ratio of the die material to electrode material exceeds 5 to 1. The surface finish obtained from graphite is as fine as, if not finer than, brass. Graphite is also lighter than brass which facilitates handling during machining of the blank and reduces weight on the ram during EDM. The cost of graphite is higher than that of brass. However, considering the metal removal rate of graphite as compared to brass, the overall cost of graphite electrodes is less. Considering these facts, graphite was selected as the material for the electrodes.

The graphite selected for the near-net tooth electrode was Poco-2. This material was selected because of its strength and smaller particle size and because it offers the advantage of producing a finer surface finish in the die cavity. The electrode blanks for both trials were turned in a lathe using normal machine practices.

The tooth form was cut into the electrode blanks using a No. 28 Gleason gear generator. The settings of the gear cutting machine were obtained from the output of the computer program SPBEVL and are as follows.

NEW VALUES FOR MACHINING GRAPHITE ELECTRODES  
ON NO. 28 GENERATOR FROM SPBEVL PROGRAM

BLANK DIMENSIONS	OLD VALUES	NEW VALUES
Number of Teeth	39	39
Pressure Angle	20D OM	20D OM
Spiral Angle	35D OM	35D OM
Face Angle	78D 3M	78D 3M 34S
Pitch Angle	77D OM	77D OM 37S
Dedendum Angle	3D 44M	3D 43M 51S

BLANK DIMENSIONS	OLD VALUES	NEW VALUES
Outer Cone Distance	8.467	8.661
Face Width	2.625	2.685
Addendum	0.148	0.151
Dedendum	0.604	0.617
Distance Between Crossing Point and Cone Apex	0.000	0.000
Mounting Distance	3.312	3.385

CUTTER DATA

Cutter Diameter	12.000 inch	12.275 inch
Point Width	0.250 inch	0.243 inch
Outside Blade Angle	20 D OM	20 D 2M 2S
Inside Blade Angle	20 D OM	19 D 59M 30S
Outside Blade Radius	0.130 inch	0.133 inch
Inside Blade Radius	0.130 inch	0.133 inch

MACHINE SETTING

Machine Root Angle	74D 24M	74D 24M 43S
Machine Center to Back	MD-0.214	MD-0.219
Sliding Base	0.000	with .010
Blank Offset	0.000	0.000
Eccentric Angle	53D 53M	55D 13M 23S
Cradle Angle	343D 51M	344D 31M 12S
Decimal Ratio	0/0/0/0	0/0/0/0

Those new values given above (i.e., new blank dimensions, new cutter data, and new machine settings) were predicted by the program SPBEVL, considering corrections due to loading, shrink fitting of the dies, and temperature differentials between the gear blank (1150°C) and the forging die (176°C). The new cutter specifications given above were approximated to the second digit, since three digit accuracy would be very difficult to obtain during the production of these cutters. Therefore, the new specifications of the cutter used in machining the electrodes are as follows.

#### SPECIFICATION OF CUTTER USED

Cutter Diameter	12.270 inch
Point Width	0.240 inch
Outside Blade Angle	20 D OM

#### SPECIFICATION OF CUTTER USED

Inside Blade Angle	20 D OM
Outside Blade Radius	0.130 inch
Inside Blade Radius	0.130 inch

5.3.7. Forging Trials. Forging of the near-net drive gears was performed at the Eaton Forge Division in Marion, Ohio. In the initial forging trials of this phase, 13 gears were forged to evaluate the forge tooling design and the induction heating system. The preforms were heated to approximately 2100°F in the induction coil described in an earlier section of this report and forged in Eaton's 8000 ton forging press. The arrangement of the press and coil is shown in Figure 5-16. After forging, the gear was placed with the teeth down in a sand-graphite mixture for cooling.

During the trials, a considerable amount of scale formed on the preforms prior to forging. The scale resulted from the long heating times required with the induction coil initially designed for these trials. The induction coil and heating system was redesigned before the final forging trials for more rapid, scale-free heating. The major modification in this improved system was a coil design that permitted heating from both inside and outside of the ring. This reduced the heating time from approximately 20 minutes to 8 minutes.

As before, the coil was placed in the frame of a material handling mechanism which was used to lift the billet into the coil. The billet was placed on a high temperature refractory material which sealed the coil, allowing the neutral atmosphere to be trapped. The coil was coupled to an induction generator which balanced the voltage to permit uniform heating.

During these forging trials, 34 forgings were produced having far better surface finish than the earlier forgings. The revised heating method produced preforms with minimum scale. The die design and ejection mechanism worked without difficulty, allowing the part to be easily removed from the die. A forging produced in these trials is shown in Figure 5-17.

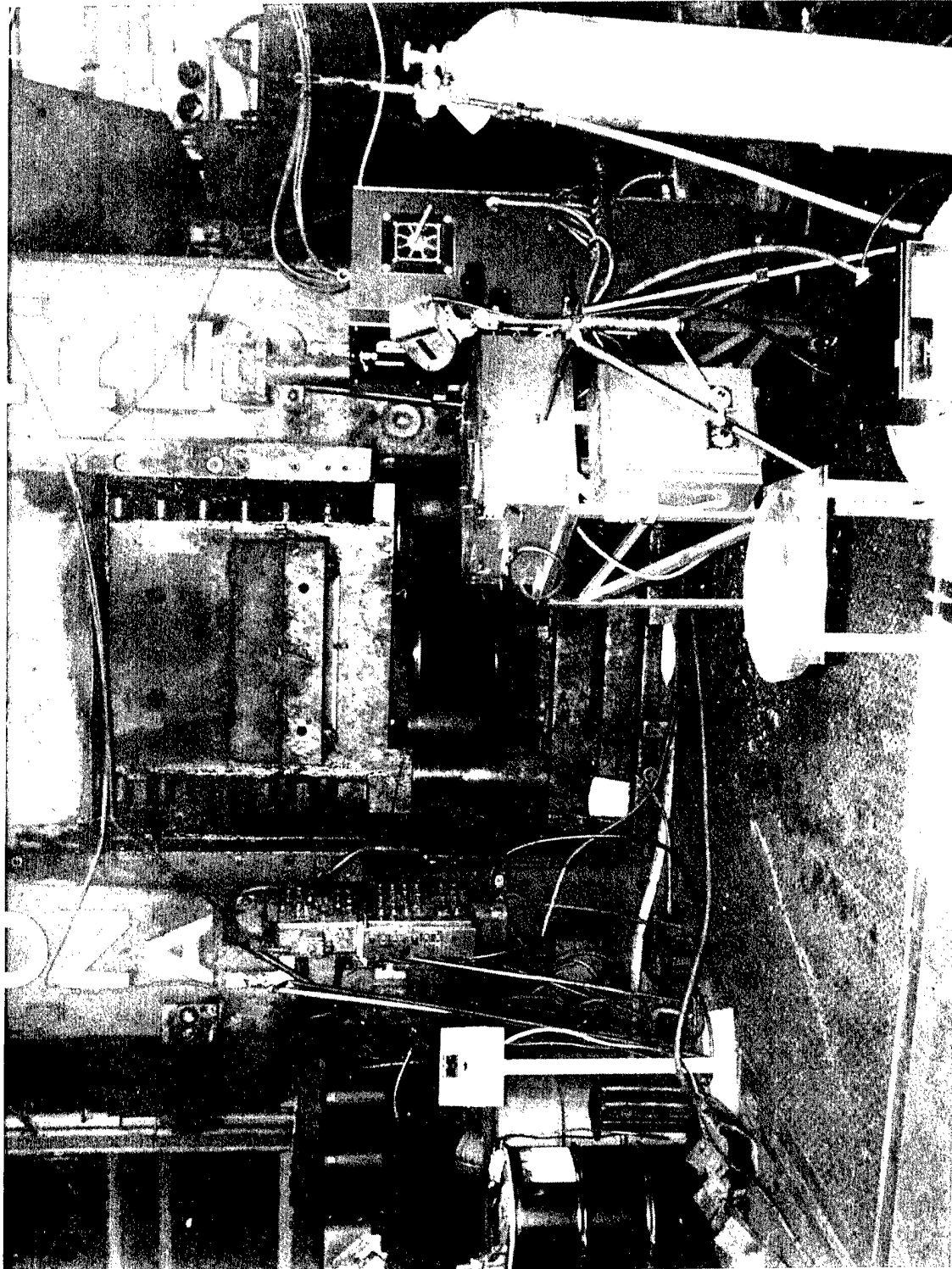


Figure 5-16. Eaton's 8000 Ton Press During the  
Spiral Bevel Gear Forging Trials



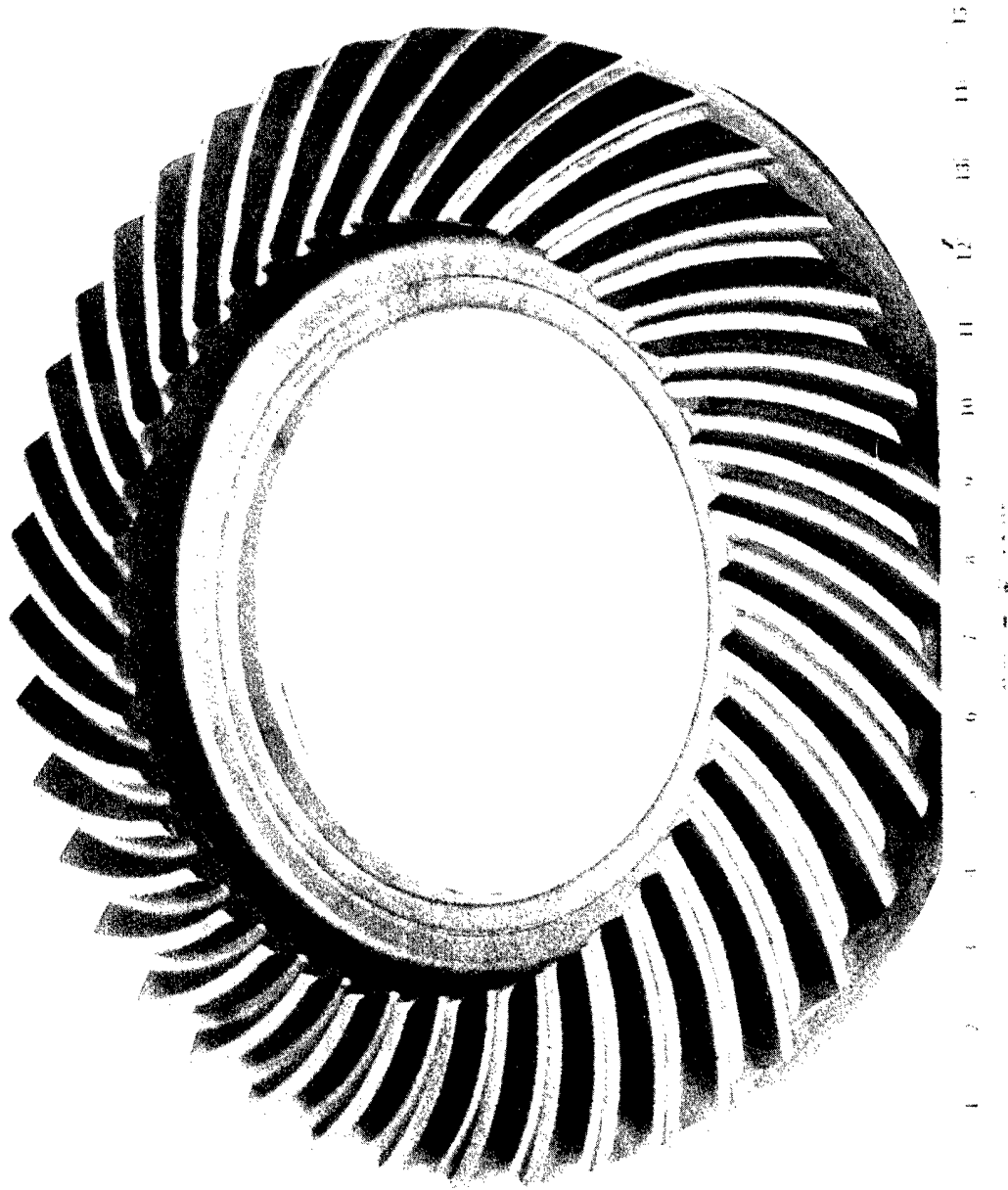


Figure 5-17. Forging Produced in this Phase of the Program

5.3.8. Inspection of the Forged Gears. Before performing the dimensional inspections on the forged gears, the gears were sandblasted to remove scale and clean the surfaces. Sample gears were then checked for dimensional accuracy on the Zeiss coordinate measuring machine (manufactured by Carl Zeiss, Oberkochen, West Germany, Figure 5-18). The Zeiss machine is a numerically controlled coordinate measuring machine used for precision measurements of gear tooth surfaces. During measurement, the gear was clamped on the machine table representing the X-slide. The column carried the probe head and was mobile in the Y-direction.

The probe head itself moved in the Z-direction. Measuring spiral bevel gears on the Zeiss multicoordinate measuring machine offers many advantages over conventional gear measuring devices in terms of the recording of measured values, reduced uncertainty of measurements, convenience of operation, and degree of automation. In contrast to conventional gear measuring techniques, multicoordinate measuring machines use no mechanical transfer elements for coupling the rotational and translational movements. All the necessary movement sequences for tracing involute or tooth angles are embodied digitally with high resolution (0.2 or 0.5 m) and are related to each other by the computer. Measurements of pitch take place with the computer-controlled rotary indexing table, which is completely integrated into the machine function. Its resolution is 0.5 seconds of arc at a measuring uncertainty of 1 second of arc.

To evaluate the dimensions of the forged spiral bevel gears using the Zeiss machine, it is necessary to first measure a cut master gear and store the measured coordinates in the computer memory. The forged and cleaned gear is then measured and its coordinates are automatically compared to the nominal reference points of the master cut gear. The results (differences between the gear and master) are then plotted in a graphical form. Figure 5-19 shows the plot of one tooth on a forged gear, relative deviation of the forged tooth profile from the master gear tooth produced by conventional cutting on a Gleason generator. Note that the relative error at the center of the profile is zero, i.e., the variations were measured relative to the center of the coast and drive surfaces of the master gear. The scale of the relative error is shown at the left side of Figure 5-19. The plots show the net forged gear tooth form with a maximum variation of 0.005 inches (0.127 mm).

The plot also shows that the pressure angle is accurately reproduced and the error is almost totally spiral angle error. Thus, it is expected that this error can be easily corrected in future die designs.

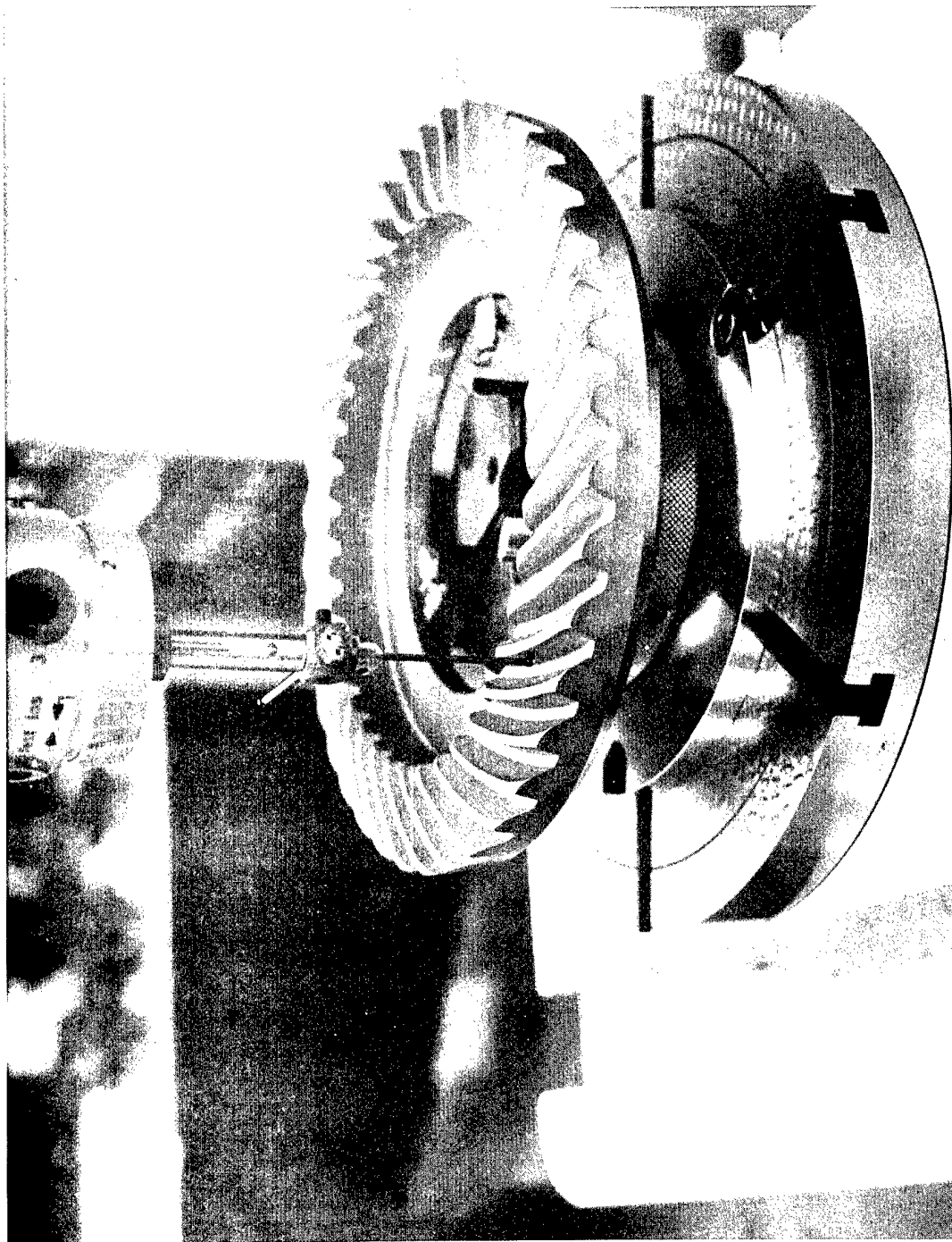


Figure 5-18. A Near-Net Spiral Bevel Gear Forging  
On the Zeiss CMM

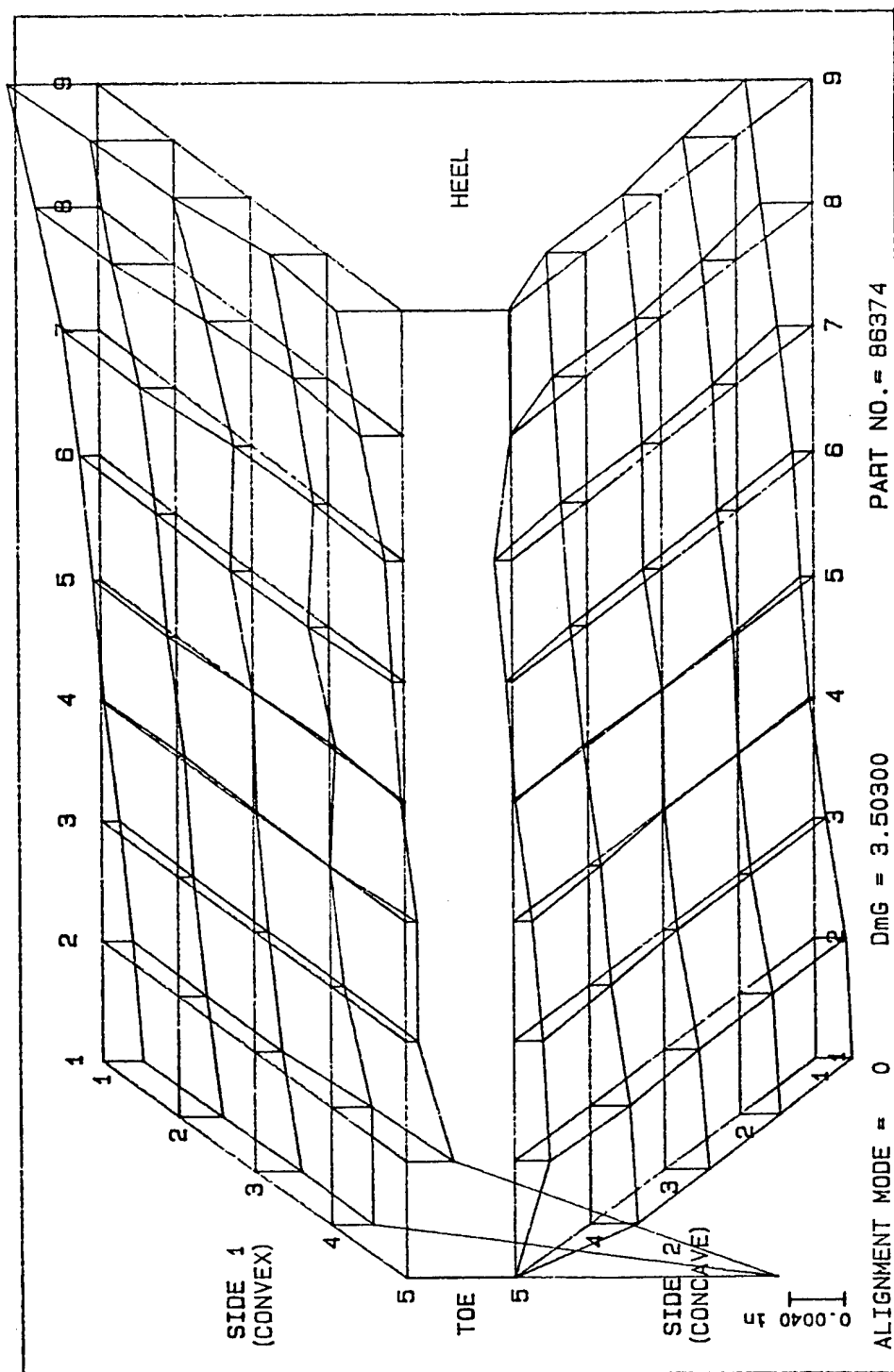


Figure 5-19. Zeiss Plot of One Gear Tooth on the Near-Net Forged Gears Relative to the Theoretical Tooth

5.3.9. Finish Processing. After inspecting the gears, the initial machining of forged gears was necessary to qualify (or center) the back face and the bore of the gear relative to the forged teeth. This procedure is different than the sequence normally used when the gears are conventionally machined. In that case, the entire forging is machined on all surfaces and then the teeth are cut with respect to the bore. In the forgings with near-net teeth, however, special problems exist that must be considered through the final machining.

The major consideration in the initial machining is to be sure that the back and bore are in proper orientation with respect to the teeth. To achieve this, it is necessary to do the initial machining with the forgings clamped in a nest located on the pitch line of the teeth. For these forgings, the ball nest shown in Figure 5-20 was used. The forging was clamped on the backface near the outside diameter while the bore and back face were machined. Without removing the forging from the nest, clamps were placed on the bore, the OD clamps were removed and the outside diameter was machined. Thus, the OD, backface, and the bore were all accurately machined with respect to the forged teeth. The machined forging, prior to finish machining of the teeth, is shown in Figure 5-21.

After machining the bore and backface of the forged gears, the gears were put into a 645 Gleason gear generator for finish-machining of the teeth. For these forgings the finish-machining of the teeth was done in two steps. In the first step, a roughing cut was made that corrected the spiral angle error. The second step was a finish-machining operation that produced the final tooth form.

After machining, the gears were processed to finish gears in the same manner as would be used for conventional gears. The gears were heat-treated at the Eaton Axle Division plant in Glasgow, Kentucky. After heat treatment, the gears were lapped to match conventional pinions to the gears. Ten complete sets (one ring gear and one pinion gear in each set) were delivered to TACOM for evaluation.

## 6.0. CONCLUSIONS AND RECOMMENDATIONS

The major goal of the program was to demonstrate that the close tolerance forging process, combined with CAD/CAM, was an attractive and economical method for manufacturing spiral bevel gears. To achieve this goal, the use of advanced CAD/CAM techniques to design and manufacture the forging dies was necessary. In applying the CAD/CAM techniques to spiral bevel gear forging, the following results were achieved:

- In Phase I of the project, the gear geometry was generated based on the kinematics of spiral bevel gear-cutting machines. This was necessary since these gear-cutting machines were used to cut the electrodes to EDM the dies.

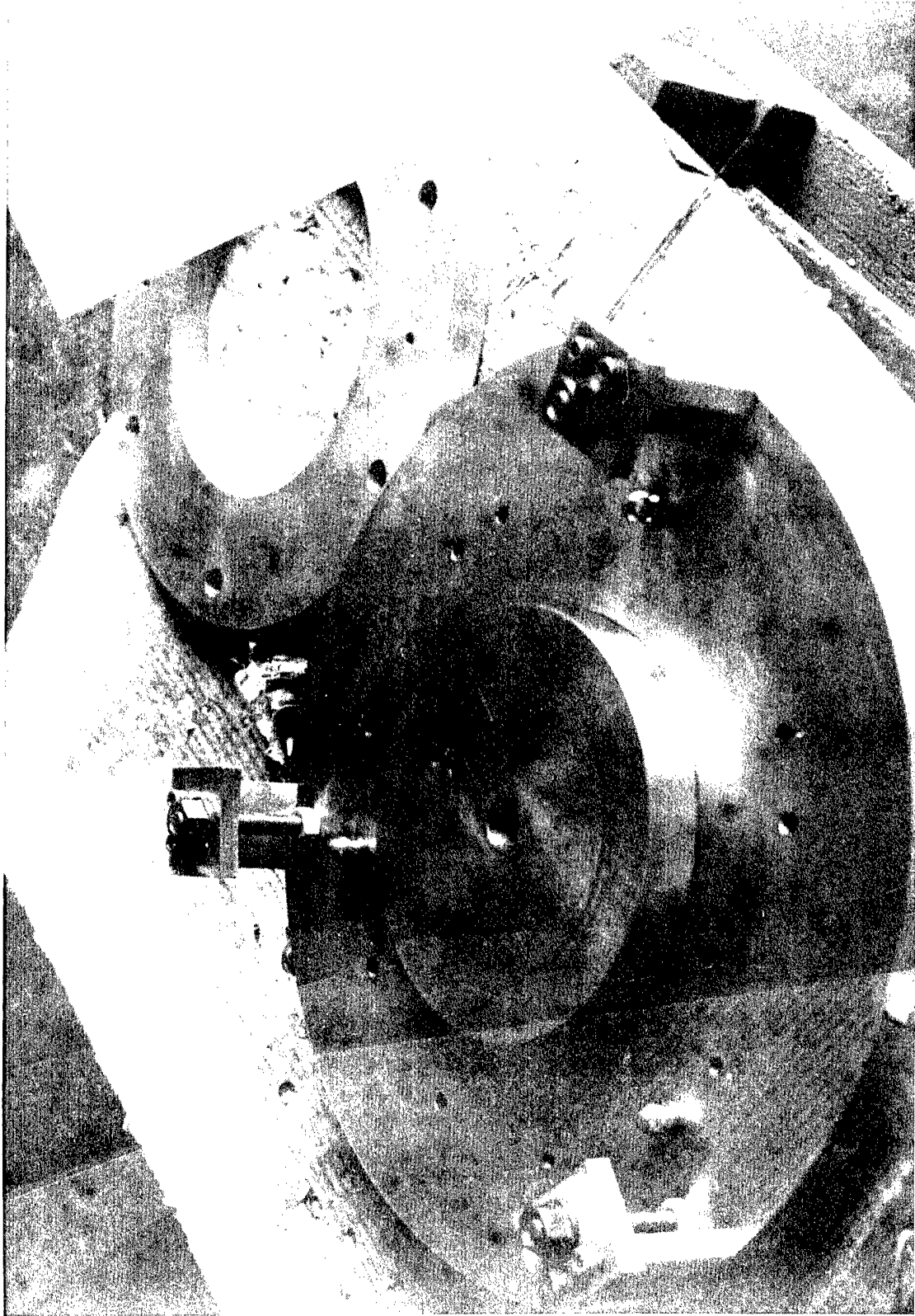


Figure 5-20. Ball Nest Used to Locate the  
Forging for the Initial Material

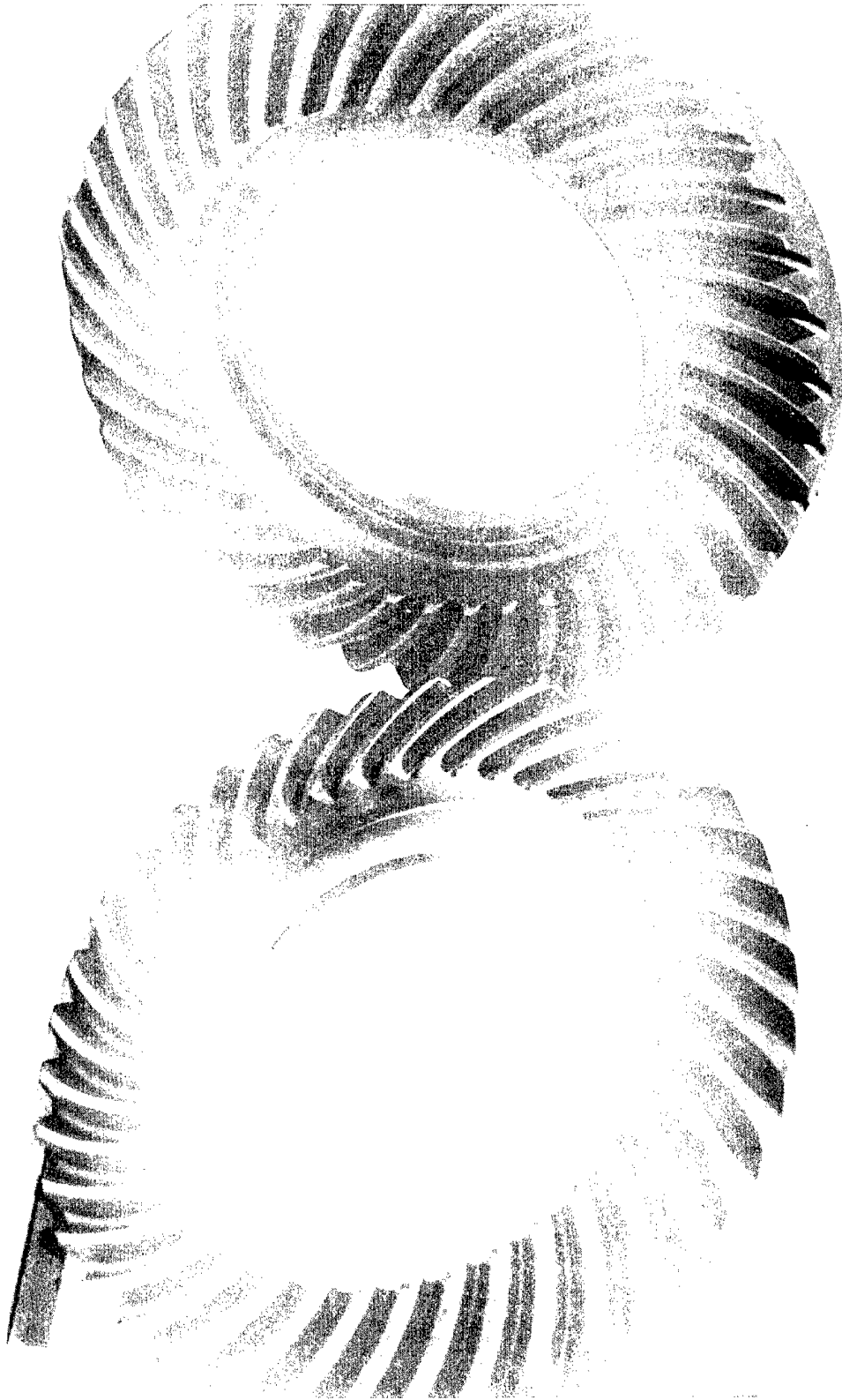


Figure 5-21. Forging Produced in this Program  
Before and After the Machining of  
the Reference Surfaces

Dimensional variations of the dies, due to thermal shrinkage and elastic deformation resulting from thermal and mechanical loading, were also calculated and integrated into the general computer program SPBEVL. The output of the SPBEVL program was the new machine settings to be used to cut the electrodes necessary for EDMing the forging dies. The results of Phase II activity indicated that the use of CAD/CAM in precision forging of spiral bevel gears is a practical technique and would reduce manufacturing costs.

- In Phase II of the project, the forging dies were designed and manufactured based on the results of Phase I for a selected spiral bevel gear. Thus, the integration and the application of the CAD/CAM process was achieved and demonstrated. Forging trials conducted indicated that close tolerance forging of spiral bevel gears, requiring a single finishing operation, is feasible and can be implemented in production. Dimensional accuracy of gears as measured with a computer-controlled coordinate measuring machine indicated excellent agreement between the geometry of forged gears and the corresponding machined gears manufactured conventionally.
- In Phase III of the project, a very large commercial gear of 16.5 inch (420 mm) diameter was chosen. Dies were designed following the same procedure as the previous phase. The die design was, however, inverted to have the teeth on the ram to ensure proper filling of the teeth. More than 30 gears were forged with a newly designed preform and the induction heating apparatus. Dimensional checks performed indicated that the forged teeth had a maximum variation of 0.005 inch (0.127 mm). The pressure angle was accurately reproduced and the total error was due to the variation of the spiral angle.

The results of the project indicate that the use of CAD/CAM in close-tolerance forging of spiral bevel gears is a practical technique and would probably reduce manufacturing costs.

The class of gears considered in the current program belong to the category of FORMATE (Trademark of Gleason Works, Rochester, New York) gears cut on Gleason 26 and 28 generators. Extension of this technology to other types of gears with generated geometry such as with modified roll and tilt mechanism will be very useful. Consideration of other gear-cutting machines such as Klingenberg and Oerlikon will also serve a large group of industries.

From the point of view of implementation in the industries, forging the teeth to near-net tolerances with finishing after hardening (either by machining or grinding) will be most probably the method of manufacture of this category of gears in five years. Computer-aided techniques such as the one developed in this project will lead the way in adapting the technology in a production environment.



## LIST OF REFERENCES

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APPENDIX A

BUDGETARY COST ESTIMATE FOR PRODUCTION

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## A-1.0. INTRODUCTION

A budgetary cost estimate for production (BCEP) was completed for the production of spiral bevel gears using CAD/CAM methods for die design in precision forging. Table A-1 summarizes the BCEP for each of the required yearly production quantities of the gear forged in Phase III of the research program. The specific monthly production rates are also given in the same table. Listed below are the individual elements of the BCEP for the manufacture of precision forged spiral bevel gears.

## A-2.0. BCEP COST ELEMENTS

The cost estimate given here is based on the best production conditions. Actual production costs may vary depending upon production experience concerning scrap, die life, and other manufacturing variables.

### A.2.1. Nonrecurring Investment

A.2.1.1. Initial Production Facilities. Initial toolings a) for the preparation of billets by either shearing or sawing in the amount of \$ 50,000, b) for making the preform in the amount of \$ 25,000, and c) for the actual forging in the amount of \$ 275,000 will be required. Further an induction heating apparatus at a cost of \$ 100,000 will be required. The estimated cost of an 8,000 ton mechanical press needed to forge the selected gear is \$ 4,500,000. A screwpress which could be used to forge the same gear will cost approx. \$ 4,000,000. In addition, machining (turning) equipment costing around \$ 400,000 will be required. Support inspection equipment to the tune of \$ 50,000 is also needed.

A.2.1.2. Other Nonrecurring Investment. There are no other nonrecurring investment items.

TABLE A-1. Budgetory Cost Estimate for Production of Various Yearly Quantities, and Monthly Production Rates

Yearly Quantity	Monthly Production	Unit cost Dollars
2,400	200	180.88
6,000	500	174.63
12,000	1,000	172.29

### A.2.2. Production

A.2.2.1. Manufacturing. The following costs per part would be incurred in the fabrication and check out of the product:

Parts/year

	2,400	6,000	12,000
	-----	-----	-----
	\$	\$	\$
Material	21.00	21.00	21.00
Labor			
Set-up	0.42	0.21	0.18
forging+machining	3.48	3.48	3.48
Tooling cost	2.20	2.20	2.20
Overhead	78.00	73.80	73.20
Scrap	2.34	2.01	1.00
Packaging	0.60	0.60	0.60

There would not be any government furnished equipment required. The gears should be delivered as a pair with the mating pinion. The costs for the pinion, heat treatment, and the final lapping of both the gear and the pinion are not included here.

A.2.2.2. Recurring Engineering. The cost of all engineering in support of production is included in the overhead charge.

A.2.2.3. Other Production. The cost associated with quality control is included in the overhead rate.

### A-3.0. DERIVATION OF THE BCEP

Figure A-1 shows an estimate of the learning curve for the production of precision forged spiral bevel gears at an estimated yearly production rate of 12,000 gears. Efficiency improvement is estimated at 15% over a one year period and 5% for the next three years. Costs are plotted for constant dollars.

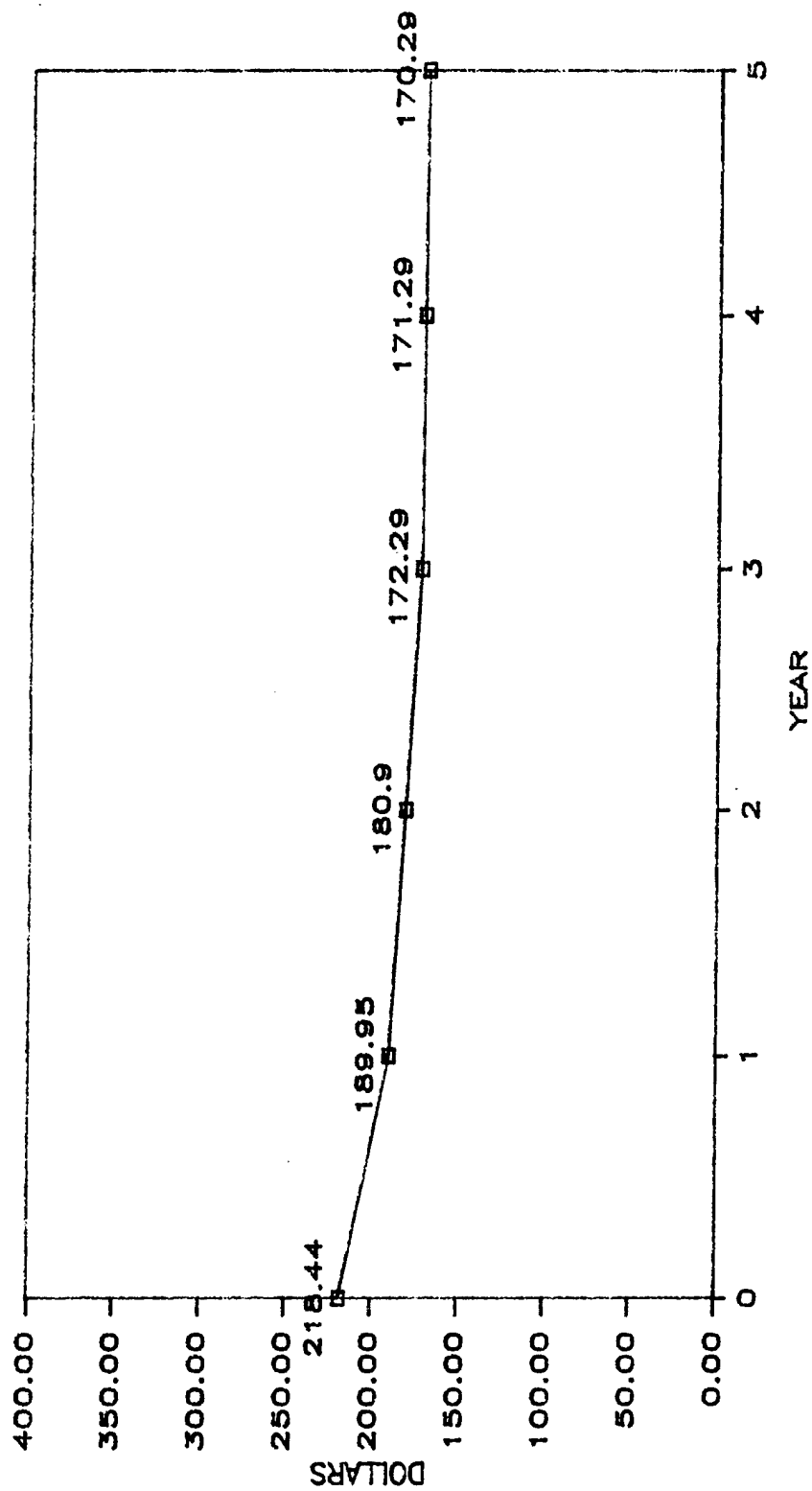


FIGURE A-1. ESTIMATE OF THE LEARNING CURVE FOR THE PRODUCTION OF PRECISION FORGED SPIRAL BEVEL GEARS AT AN ESTIMATED YEARLY QUANTITY OF 12,000 GEARS (DOLLARS VERSUS YEARS)



#### A-4.0. CRITICAL PROCESSES

In any manufacturing process in which parts are to be produced to net or near net tolerances, extreme care must be taken in all tool fabrication and in the production processes. The major issues that require extra care and attention to details in the precision forging of spiral bevel gears are the electrode/die manufacture, and control of process conditions during forging.

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